TESTING OF MULTI-MPPT PV INVERTERS: APPROACH AND TEST RESULTS

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ABSTRACT: The European standard EN 50530 defines procedures for measuring the conversion and MPPT efficiency of PV inverters. The standard has been released in 2010 when multi-MPPT PV inverters were not yet widely-used. Therefore, the scope of EN 50530 is limited to PV inverters with only one MPP tracker. Today however, multi-MPPT inverters have become a market standard. The question is now what tests are necessary to obtain a good characterization for these devices. The easiest approach would be to simply use the test profiles defined in EN 50530 on each of the inverter's inputs simultaneously. But by doing so, one would disregard the main purpose of the multi-MPPT technology: to achieve a good performance under inhomogeneous conditions. Therefore, measurements with different test profiles on each MPP tracker should be performed as well. This work proposes some modifications for existing test standards and new methods for testing of multi-MPPT PV inverters. It also presents actual measured data of real inverters, which have been tested on BFH's multi-MPPT inverter test bench.
Keywords: Inverter, Qualification and Testing, MPPT Efficiency

1 INTRODUCTION

Even though the PV inverter is one of the most important parts of a PV power plant, proper testing and characterizing of such devices has been neglected for a long time. In the past, the PV inverter's only quality feature that has been paid some attention to was the conversion efficiency. Other characteristics, namely the MPP tracking efficiency, have either been neglected or assumed to be ideal – an assessment that in many cases is far too optimistic. Because of this, many flaws in such devices have not been localized and have caused a considerable loss in energy yield. This was at a time, when the price per watt of a PV array was a multiple of what we pay today. Only in 2010, the European standard EN 50530 has been released [1]. This standard defines test procedures for the overall efficiency of grid connected PV inverters including conversion and MPPT efficiency with both static and dynamic test profiles. When EN 50530 was first released, multi-MPPT PV inverters were not yet very popular. Consequently, the scope of this standard does not include multi-MPPT inverters. Today however, many modern PV inverters have at least two MPP trackers. Technically, multi-MPPT inverters are now in the same position as single-MPPT inverters have been before the release of EN 50530. Of course it is possible to adapt the existing normative test profiles and use them on each MPP tracker simultaneously (which actually is the current standard procedure). But this allows only a partial characterization of the inverter. The main reason for the multi-MPPT technology is to achieve a good performance under inhomogeneous conditions (e.g. in a plant with multiple module orientations, different number or modules per string or partial shading). This very feature cannot be tested with the existing normative test procedures.

2 PV INVETER TESTS AT BFH'S PV-LAB

The PV-Lab of BFH is one of the first and most experienced testing centers for PV inverters in Europe. Already in 1994, first tests on grid connected PV inverters were performed. Compared to the devices we have today, these early PV inverters were downright primitive. In these first years, PV inverter tests at BFH have been performed with an on-side PV array of 60kWp. However, it soon became clear that a good qualification of a PV inverter (especially of the MPPT performance) is only possible under highly stable and reproducible test conditions. With a real PV array, this is not possible. Therefore, since 1999 tests have been performed with PV array simulators. After having made bad experiences with a commercially available simulator, BFH's PV-Lab began developing its own PV array simulators. Today, the PV-Lab has a well-equipped inverter test stand with two single-string simulators (20 kW & 100 kW) and one multistring simulator (3 x 11.5 kW). The accreditation of the test stand is underway [2, 3].

3 EXISTING TEST PROCEDURES

EN 50530 defines test profiles for both static and dynamic conversion and MPPT efficiency measurements. The aim of the static measurements is to determine the inverters conversion and tracking performance under steady-state conditions. For this, the inverter is being measured while operating at different voltage and power levels. The essence of these tests is the European efficiency (η_{EU}) which is a weighted average of the individual measurements and is a good approximation for the device's average performance in the central European climate. In the same manner but with different weighting factors, the CEC efficiency (η_{CEC}; California energy commission) is calculated. These measurements are performed at three voltage levels (namely at the minimum, the rated and the maximum MPP voltage). The conversion efficiency of many PV inverters has a high dependency on the device's operating voltage. Sadly, many manufacturers specify the European efficiency at the optimum MPP voltage only – and often they do generously round up the value (+0.2% or so are standard).

The aim of the dynamic measurements is to show how good the inverter's MPP tracking algorithm can adapt the device's operating point to a non-static maximum power point. For this, the inverter is being measured while operating with test profiles with a time-variant simulated irradiance (the cell temperature is assumed to be constant). The simulated irradiance describes linear ramps between different irradiance levels and with different slopes. The goal of this is to simulate both slow and fast variations in irradiation. Tests at BFH's PV lab show that even modern PV inverters occasionally have problems following the MPP at several slopes, leading to a loss in tracking efficiency.

4 EXISTING PROBLEMS AT MEASURING THE EUROPEAN AND CEC EFFICIENCY AND PROPOSED SOLUTION

If the MPP power of the simulated PV array is higher than the inverter's rated power, the inverter usually reduces its input power by moving the operating point out of the MPP. As the operating point is then no longer in the MPP, the MPPT efficiency becomes very poor. In the measurements required for the calculation of η_{EU} and η_{CEC}, one measurement must be performed at the inverter's rated power. If for some reason the MPP power of the simulated PV array is slightly higher than the inverter's rated power, the device will limit its input power. This has a negative impact on the MPP tracking efficiency. This can easily happen if for an instance the PV array simulator cannot be programmed with the accuracy required. If the inverter's manufacturer specifies the rated AC power only (this is very common) the rated DC power must be estimated using the specified conversion efficiency. In such cases the MPP power of the PV array simulator can easily be 1-2% too high. This will lead to a very low MPP tracking efficiency and an unfair test result. To prevent this systematic error, the highest power level in the measurements required for η_{EU} and η_{CEC} should not be at 100% of the inverters rated power, but rather at 95%. This modification would only have a minimal effect on η_{EU} and η_{CEC} under normal conditions. A similar problem can occur because of the MPP voltage used for the tests. Some of the measurements have to be performed at the inverter's minimum or maximum MPP voltage. Because it is not a good practice to characterize a device at its limits, these measurements should be performed at e.g. 105% of the minimum and 95% of the maximum MPP voltage. Moreover, if the the inverter's maximum MPP voltage is too close to its maximum DC voltage, technically the test cannot be performed. According to EN 50530, the simulated PV array has a ratio of 0.8 between the MPP voltage and the open circuit voltage. If the inverter's maximum DC voltage is not at least 25% higher than its maximum MPP voltage and the MPP of the simulated PV array is at the inverter's maximum MPP voltage, the open circuit voltage of the PV array is higher than the inverter's maximum DC voltage. This might damage the inverter. The author's proposition in such cases is to choose the maximum MPP voltage for the static measurements no higher than 75% of the inverter's maximum DC voltage. Frankly speaking, no reasonably designed PV plant should have its nominal MPP voltage at more than about 75% of the inverter's maximum DC voltage, because the inverter should also survive the array's open circuit voltage at cold temperatures. Unfortunately, many PV inverters have a specified ratio between maximum MPP voltage and maximum DC voltage that is much higher. Some manufacturers even specify these two voltages to be identical (which is nonsense). This might mislead overeager plant designers to design the PV array with voltages too high for the inverter in use [4].

5 MISSING TEST PROCEDURES IN EXISTING STANDARDS AND PROPOSAL FOR A NEW TEST WITH A PARTIALLY SHADED PV ARRAY

The existing test procedures described in EN 50530 allow a good characterization of a single-MPPT PV inverter as long as it is connected to a completely unshaded PV array. Such an array has a P/V characteristic that is a continuous curve – just like the normative test curves in EN 50530. However, when a PV array is partially shaded, the array's P/V characteristic can have one or more local maxima aside from the actual MPP. In this situation it can happen that the inverter's operating point is stuck in one of these false peaks. It is even possible that due to changes in the partial shading, the MPP can change from one local maximum to another. Some inverters have problems to follow these changes of the MPP's position. They keep their operating point in the formerly correct but now false maximum. In such cases, considerable tracking losses (>>10%) for time periods of up to several hours are possible. Despite these potentially severe losses, this scenario is not covered by the existing test procedures in EN 50530. Here, a new test is proposed. This test is based on a simulated PV array with a fill factor of 72% (model according to EN 50530). Open circuit voltage and short circuit current of the array are set so that the MPP (under STC conditions) is at the inverters rated voltage and DC power. At the beginning of the test, the entire PV array is irradiated with 160 W/m^2. This is a realistic value for shaded PV modules on a clear day. After a settling time, which allows the inverter to start up and find the MPP, the irradiation on 80% of the modules (which are in series to the remaining 20%) begins to rise with a slope of 0.4 W/m^2 per second. After 1'600 seconds the irradiation on this (now unshaded) part of the array reaches 800 W/m^2. Then the test is complete. After 45 seconds, when the simulation on the unshaded part of the array reaches 178 W/m^2, a second local maximum forms on the P/V curve. When the simulated irradiation on the unshaded part of the array is about 231 W/m^2 – that's 178 seconds after beginning of the slope – the MPP makes a jump from the original maximum to the new one. A good MPP tracker should be able to quickly change the inverter's operating point to the new MPP, whose voltage is about 25% lower than the former MPP's voltage. After the jump of the MPP, the irradiation on the unshaded part of the array continues to rise for 1422 seconds, which is somewhat more than 23 minutes. That is enough time for a good MPP tracker to find the new MPP. However, an MPP tracker that remains in the false local maximum will harvest less than 48% of what would be possible. Figure 1 shows some P/V characteristics of the proposed test array. The values are normalized to the open circuit voltage and short circuit current at STC. Due to this normalization, if the array was under STC, short circuit current and open circuit voltage would be one and the MPP power would be equal to the fill factor. Three curves are plotted. The dark blue curve is the P/V characteristic at a homogeneous irradiation of 160 W/m^2. This curve is continuous and has only one maximum. That is the situation during the settling time and at the beginning of the test. The red curve represents the characteristic when the irradiance on the unshaded part of the array is 231 W/m^2. Here, both maxima have the same value. This is the moment when the MPP jumps from the right to the left peak. The purple curve shows the characteristic at the end of the test, when the irradiation on the unshaded part of the array is 800 W/m^2. Pay attention to the power difference of the two maxima. An inverter with its operating point stuck in the false peak would lose about 69% of power in this final situation.

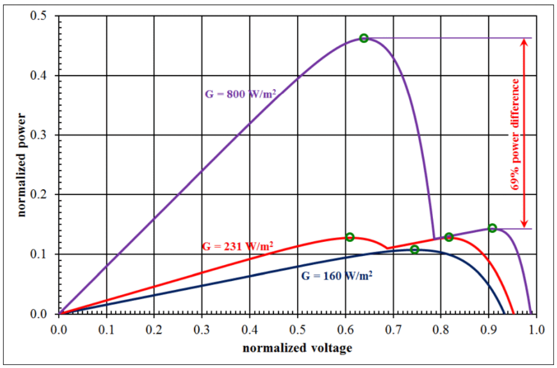

Figure 1: P/V characteristics of the partially shaded test array with different irradiations

Figure 2 shows power and voltage of the two maxima of the P/V curve as a function of the time. The values are normalized in the same manner as in Figure 1. The solid lines represent voltage and power of the actual MPP. The dashed lines represent voltage and power of the other peak. Remarkable is the drop of the MPP voltage at 178 seconds, when the MPP jumps from one peak to the other. Finding the actual MPP again is a demanding task for the device under test.

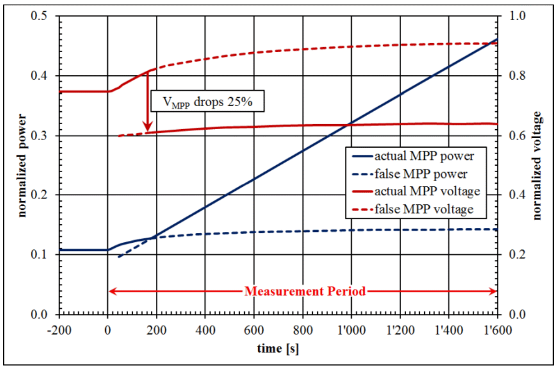

Figure 2: Voltage and power of the actual MPP (solid) and the false local maximum (dashed)

One might criticize that this test is not realistic, because a linear ramp of irradiance on the unshaded part of the PV array does not occur in reality (especially when the irradiation in the shade is constant). In reality, a shadow usually moves over the array. So it's rather the number of modules that is shaded and not a variation of the irradiance that influences the resulting P/V characteristics. However, to keep the test simple but fair, a compromise must be made (this is also done in some of the tests in EN 50530 and many other standards). A major problem of scenarios with moving shadows on a PV array is that the MPP voltage can fall to very small values (e.g. 10-20% of the MPP voltage at STC). This is outside of the tracking window of most PV inverters. Consequently, the device under test has no chance to properly track the MPP and achieve a good test result. Such a test is unfair and the result is not representative for the device under test. Of course, this is exactly what can happen in reality. But then the error rather lies in the design of the PV array and is not a flaw of the inverter (granted, modern PV inverters are good, but you cannot expect them to perform "magic"). It is the belief of the authors that this test is close enough to the reality, but still strict enough to unveil problems in MPPT algorithms. It is a chance to localize one of the last major sources of errors in PV systems with both single- and multi-MPPT PV inverters.

6 EQUIPMENT NEEDED FOR TESTING OF MULTI-MPPT PV INVERTERS

Compared to single-MPPT PV inverters, much more equipment is needed for testing multi-MPPT PV inverters. Two main components are needed to determine the MPPT performance: A high precision power analyzer and a highly stable PV array simulator. Measuring the MPPT efficiency means to compare how much energy a PV inverter draws from a PV array (or simulator) in a certain amount of time to the amount of energy that would have been available in said amount of time. The latter is the integral of the MPP power over the measurement period. Because of this, the MPP power of the simulated PV array must be known exactly at any time of the test. Consequently, accuracy and stability (mainly the thermal drift) of the PV array simulator set a limit to the uncertainty of the measurement. Therefore, a highly stable PV array simulator is essential for this measurement (drift < 0.1%). However, such a high stability is a very strict requirement for a power electronic device like a PV array simulator. For testing multi-MPPT PV inverters, one such simulator is required on each MPP tracker. Moreover, each of these inputs must be measured with a separate channel of a precision power analyzer. As most multi-MPPT PV inverters are three-phase devices, three more power measurement channels are needed for measuring the AC power. The measurement periods of all these devices must be synchronized exactly.

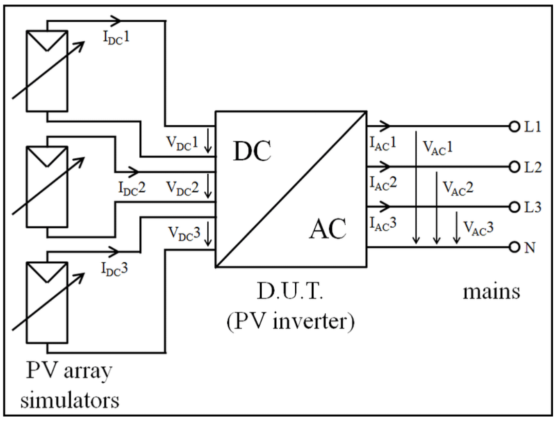

Figure 3: Test setup for a PV inverter with three MPP trackers and a three-phase output

Figure 3 shows an exemplary test circuit for a three-phase PV inverter with three MPP trackers. In total, six currents and six voltages must be measured. Thus, six power analyzer channels are required. If the inverter had only two MPP trackers, it would still take five channels to perform the measurement. It is essential that the cable losses are compensated. For this, all voltages must be measured directly at the inverter's terminals. However, the cable losses also have a slight impact on the MPP's position. Therefore, the calibration of the PV array simulators must be performed at the end of the DC cables. Ideally, this is done with the same power analyzer that is used in the actual measurement. By this, any bias of the power analyzer is being compensated.

7 PROPOSED NEW PROCEDURE FOR TESTING OF MULTI-MPPT PV INVERTERS

To show the inverter's performance under inhomogeneous conditions, a new dynamic test profile is proposed. In this profile, the simulated irradiance follows linear ramps of 150 seconds duration between 100 and 800 W/(m^2*s), but the slopes on the different MPP trackers are time staggered. Again, the simulated PV arrays are modeled according to EN 50530 with a fill factor of 72%. The simulated curves are scaled so that the MPP at STC would be at the rated voltage and power of the corresponding MPP trackers. The cell temperature is assumed to be constant at 25°C. Figures 4, 5 and 6 show these test profiles for inverters with two, three and four MPP trackers.

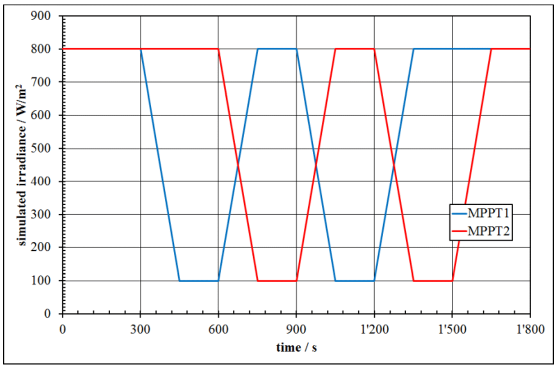

Figure 4: Test profile for two MPP trackers

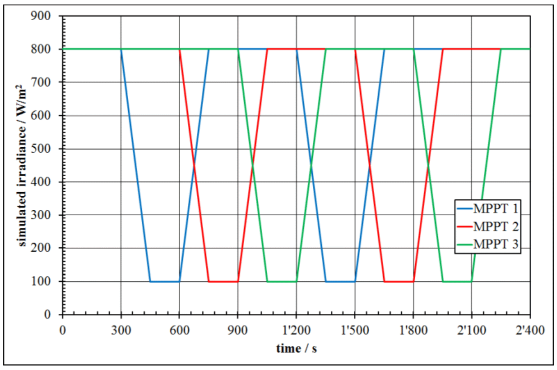

Figure 5: Test profile for three MPP trackers

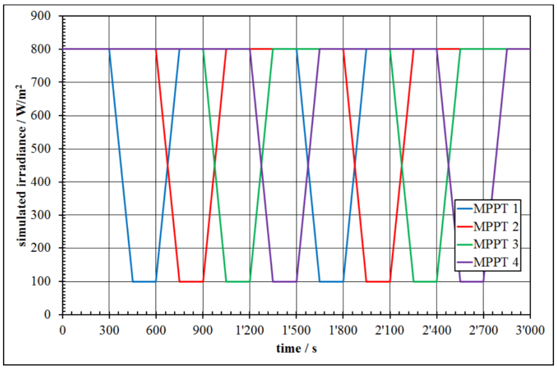

Figure 6: Test profile for four MPP trackers

If the inverter has more than four MPP trackers, the test profile of figure 6 is being used with the fifth MPP tracker having the same profile as the first, the sixth MPP tracker having the same profile as the second and so on. The test can therefore be performed with an arbitrary number of MPP trackers. Indeed, there are no PV inverters with more than four MPP trackers on the market right now (at least none that the authors knew about). Perhaps in future, there will be multi-MPPT central inverters with a dozen or so MPP trackers. With the profiles proposed here, the tests would be prepared for any such development (of course, testing of such devices would require a lot of test equipment). As the size of the simulated PV array is defined in relation to the power of the MPP tracker, devices with MPP trackers of different sizes also would not be a problem. These tests are quite simple and short, but they still allow a good characterization of the inverter under conditions, when one MPP tracker runs with a power much lower than the others.

8 SUGGESTED MODIFICATIONS IN FUTURE STANDARDS FOR TESTING OF PV INVETERS

Sooner or later, the standards for testing the overall efficiency of PV inverters (i.e. EN 50530) must be upgraded, so that their scope includes multi-MPPT inverters (note of the authors: sooner would be better than later). In this revision, the authors propose that the test procedures should be set as follows:

- Measuring the static total efficiency [5] with different voltage and power levels. The test can be adopted from EN 50530. The parameters should be adjusted according to section 4 of this paper. For multi-MPPT inverters, the tests should be performed on each MPP tracker simultaneously.
- Measuring the dynamic total efficiency. These tests can be adopted from EN 50530. For multi-MPPT inverters, the tests should be performed on each MPP tracker simultaneously. Further changes are not required.
- Measuring the total efficiency with a partially shaded PV array (see section 5). For multi-MPPT inverters, the tests should be performed on each MPP tracker simultaneously. This test is new.
- Multi-MPPT inverters only: Measuring the dynamic total efficiency under inhomogeneous input conditions (see section 7). This test is new.

9 MEASURED DATA OF ACTUAL MULTI-MPPT PV INVERTERS

Figure 7 shows the static efficiency of a PV inverter (inverter A) with three MPP trackers and a rated AC power of 15 kW. The device is manufactured in Europe. The manufacturer specifies a European efficiency of 97.5%. From this specifications, a maximum DC power of 15 kW / 0.975 = 15.385 kW can be assumed. This corresponds to 100% on the horizontal axis.

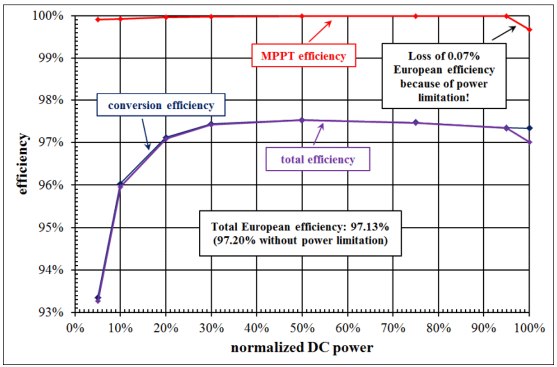

Figure 7: Static efficiency of inverter A

As you can see, the MPPT efficiency is virtually 100%. Thus, the total efficiency [5] is nearly identical to the conversion efficiency. However, in this measurement, the problem mentioned under section 4 occurred. The DC power of 15.385 kW is slightly too high for this device. Because of this, the inverter moves its operating point out of the MPP. The AC power is then limited to about 14.817 kW which is even 1.22% below the device's power rating. As a result, the MPPT efficiency (red line) drops 0.33% between 95% and 100% DC power. The total European efficiency is 97.13%. If the power limiting problem didn't occur, it would be 0.07% higher. This could easily be achieved, if for the calculation of the European efficiency the measurement point at 95% instead of 100% DC power would be used (as it is proposed under section 4). The conversion efficiency would not measurably be affected by this modification.

Figure 8 shows the same chart of inverter B. This device is manufactured in China. It has a rated AC power of 23 kW and three MPP trackers. The manufacturer also specifies a maximum usable DC power of 23.6 kW (which is 100% on the horizontal axis).

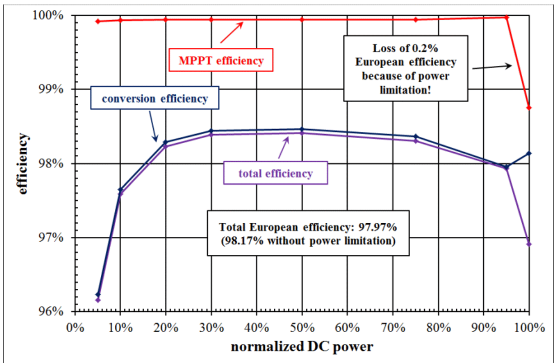

Figure 8: Static efficiency of inverter B

In this case, the loss of MPPT efficiency because of the power limitation is even higher. Even though the manufacturer explicitly specifies a DC power of 23.6 kW, the device's operating point is more than 290 W lower. Because of this, inverter B loses about 0.2% of European efficiency. Still, the measured European efficiency of 97.97% is very good. Here also, the use of the measurement point at 95% of the rated power for calculating of the European efficiency would allow a better characterization of the device. Remarkable is the rise of the conversion efficiency between 95% and 100% of normalized power. The reason for this is probably that the inverter increases the operating voltage on all three MPP trackers by about 35V to reduce the input power. At this operating point, the conversion efficiency is about 0.18% higher compared to the previous measurement point. However, this gain is far too low to compensate the MPP tracking losses caused by the power limitation. All in all, this leads to a drop of the total efficiency of more than 1% between 95% and 100% of the rated power.

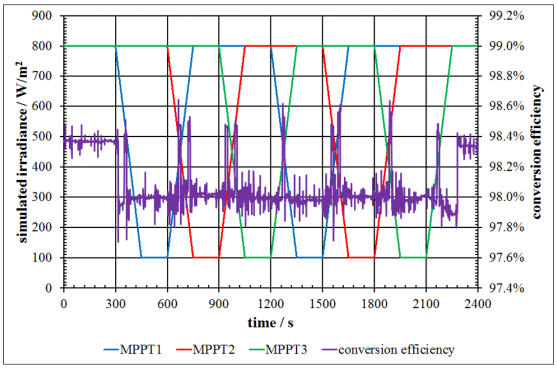

Figure 9: Conversion efficiency of inverter B with the proposed new test profile

Figure 9 shows the results of the new test proposed under section 7, performed with inverter B. As you can see, as soon as the input conditions become inhomogeneous, the conversion efficiency (purple line) drops about 0.4%. A further investigation of this problem showed that under homogeneous input conditions, all three DC inputs have the exact same voltage (except for the measuring noise). We assume that in this case, the inverter's input stages (probably boost converters) are being bypassed and all three inputs are connected directly to a common DC link. By this, the losses of the input stages can be avoided. In figure 10 you can see these three DC voltages. The picture shows a zoom of the first ramp on MPPT1.

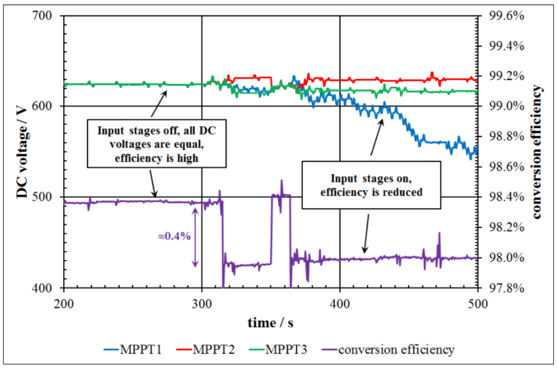

Figure 10: DC voltages and efficiency at the first ramp of MPP tracker 1

The measurements of pictures 9 and 10 show the benefit of this new proposed test profile. With the existing tests (e.g. figure 8), the loss of efficiency at inhomogeneous conditions would not have been detected. Intentionally or not, the manufacturer of inverter B makes a benefit of the current standards. But as a multi-MPPT inverter should also perform well under inhomogeneous conditions, the characterization of this device using current normative tests is not entirely representative for the operation in an actual PV array.

7 CONCLUSIONS

The test procedures in EN 50530 allow quite a good characterization of a single-MPPT PV inverter. What's missing is a test to check if the inverter has the ability to find the actual MPP on a partially shaded PV array, where the P/V curve has more than one peak. A simple test for this situation is proposed in this paper. Also, the test procedures for the static efficiency should be modified, so that no tests are being performed at the very limit of the device's specifications (voltage and power). The modifications proposed in this paper would only have a minimal impact on the test results, but they would prevent the inverter from operating in a non-representative state, e.g. with power limitation. Current standards do not include tests that are specifically designed for multi-MPPT PV inverters. Simply adapting the tests from EN 50530 and perform them on each of the inverter's MPP trackers simultaneously does not allow a good characterization of these devices, which are deliberately designed to achieve a good performance under inhomogeneous input conditions. In this paper, a simple but effective test method with inhomogeneous input conditions is being proposed. Measurements of two multi-MPPT PV inverters show that if the measurement of the static efficiency (and the calculation of the European or CEC efficiency) is performed strictly according to EN 50530, the inverter might reduce the input power at the last measurement point. This leads to a poor and non-representative MPP tracking performance. The measurement with the proposed test profile for multi-MPPT PV inverters shows that the conversion efficiency under inhomogeneous conditions can be considerably lower compared to conventional tests. Therefore, it would make sense to include this or a similar test in upcoming standards for PV inverters.

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